A Large Proper-Motion Survey in Plaut's Low-Extinction Window [1]

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Abstract. We present preliminary results from the deepest and largest photographic proper-motion survey ever undertaken of the Galactic bulge. Our first-epoch plate material (from 1972-3) goes deep enough ($V_{lim} \sim 22$) to reach below the bulge main-sequence turnoff. These plates cover an area of approximately $25' \times 25'$ of the bulge in the low-extinction ($A_v \sim 0.8$ mag) Plaut field at $l = 0°, b = -8°$, approximately 1 kpc south of the nucleus. This is the point at which the transition between bulge and halo populations likely occurs and is, therefore, an excellent location to study the interface between the dense metal-rich bulge and the metal-poor halo.

In this conference we report results based on three first-epoch and three second-epoch plates spanning 21 years. It is found that it is possible to obtain proper-motions with errors less than 0.5 mas/yr for a substantial number of stars down to V= 20, without color restriction. For the subsample with errors less than 1 mas/yr we derive proper-motion disper-

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sions in the direction of Galactic longitude and latitude of 3.378 ± 0.033 mas/yr and 2.778 ± 0.028 mas/yr respectively. These dispersions agree with those derived by Spaenhauer et al. (1992) in Baade's window.

1. Introduction

Historically, tremendous observational effort has been invested in understanding the formation of the halo and chemical evolution of the disk. Ideally, one wants to measure proper-motions, radial velocities, and abundances for members of a stellar population, inspired by the seminal effort of Eggen, Lynden-Bell & Sandage (1962). While the halo does not appear to exhibit clear correlations of abundances with kinematics (cf. Carney et al. 1990), there is some indication that metal-rich bulge stars have a smaller velocity dispersion (Rich 1990). In much larger samples of bulge giants in fields away from the minor-axis, Minniti (1993, 1996) finds abundance/kinematics trends that suggest that more metal-rich bulge giants have greater rotational support. Unfortunately, fields distant from the minor axis may be contaminated with giants at the tangent point arising from the disk population (Tiede and Terndrup 1996). The next step in confirming Minniti's findings is the careful study of a minor-axis field, including proper-motions.

These issues can be settled by correlating abundances with proper-motion and radial velocity dispersions. The geometry for viewing the bulge is favorable: we are 8.5 kpc distant from a system which has most of the mass contained within 1 kpc. We are therefore privileged to study the bulge from an almost extragalactic perspective.

Given its extreme crowding, high extinction, and southerly declination, the bulge has received substantially less observational attention than the globular cluster system. Only one proper-motion study has been undertaken (Spaenhauer et al. 1992). While a landmark achievement, their work addresses the extremely crowded Baade's Window field ($l = 0°, b = -4°$). There were three first-epoch plates, all obtained on the Palomar 200-inch telescope. Because the plates were B plates, very few late M giants were measured; these stars dominate the bulge asymptotic giant branch, and it is of great interest to compare their kinematics with bulge K giants.

Our study addresses the tangential kinematics of the Galactic bulge in Plaut's (Plaut 1970, 1971) low-extinction window ($E_{B-V} = 0.25$ mag, van den Bergh & Herbst 1974). This window, centered at $l = 0°, b = -8°$, provides a unique place to look at the Galactic bulge and its transition into the the halo of the Galaxy, as the line-of-sight crosses the Galactic minor-axis some 1.3 kpc to the South of the nucleus. Furthermore, this region has smaller reddening and is less crowded than Baade's window ($E_{B-V} = 0.42$ mag, Blanco and Blanco 1985).

The field in this study is of critical importance as it lies at the edge of the bulge (as defined, for example, by the *COBE-DIRBE* map). It has extinction $A_v = 0.8$ mag, lower than most bulge fields, and it will contain a substantial number of halo giants, allowing one to probe the bulge/halo transition. We

know little about the field population of the inner halo; this study will also fill that gap in our knowledge.

We expect to measure CCD photometry in the B, V, and I passbands, and proper-motions for an unbiased sample of approximately 30,000 stars in our minor-axis field. We hope to further obtain radial velocities and low resolution abundances for about 5,000 stars. A large, unbiased sample is important because much of the outcome depends on dividing the data into subsamples as a function of abundance or kinematics.

2. Plate material, measurements, and the proper-motions

Our project is based on a unique sample of twenty photographic plates of a Galactic bulge field on the minor-axis at $b = -8^{\circ}$ obtained by Sidney van den Bergh in 1972-3 using the Kitt Peak 84-inch and the 200-inch telescopes (van den Bergh & Herbst 1974). The 100-inch telescope at Las Campanas has been used to obtain thirteen second epoch plates in 1993; deep intermediate epoch plates of this field (1979) were obtained by Jeremy Mould also at Las Campanas (these intermediate epoch plates have not been used in this preliminary study).

The plates were digitized using the the Yale PDS 2020G laser interferometer/microdensitometer measuring machine in raster-scan mode. The aperture size was 33 μm, while the step size was 30 μm. At this step size, the faintest images will be properly sampled for the astrometric centroiding (our plates have scales on the order of 10 arc-sec/mm). All scans were performed under the best possible thermal conditions to avoid instrumental drifts during the scan. Each scan took between 8 and 10 hours. Depending on the plate scale, the digitized frames had between $4,200 \times 4,200$ $pixels^2$ and $5,600 \times 5,600$ $pixels^2$. The PDS system outputs an integer fits-file with 16 bits/pixel that is easily converted into other formats for later analysis. At this conference we report on preliminary results from reductions of only three first-epoch and three second-epoch plates.

Analysis of the Yale-PDS microdensitometer data routinely yields star centroids to 1/20 of a pixel (20 mas). A star measured on five plates in each color will have its position known at least 2–3 times better than this, and over the 21 yr baseline we expect errors no larger than 0.5 mas/yr in each color. This corresponds to approximately 20 km/s at the distance of the Galactic Center. This is comparable to Spaenhauer et al., and matches the accuracy with which radial velocities in our spectroscopic follow-up will be measured.

The first step in the process of obtaining proper-motions was to create an input catalogue of approximate stellar positions. For this purpose we selected a relatively deep second-epoch master plate with the best image and fog characteristics, requiring also that the full FOV would be available in this master plate. Then, we created a master list of candidates to perform the astrometric solution. This was done by running DAOFIND from the DAOPHOT package within IRAF. Approximate “image” parameters (FWHM) and “frame” parameters (the rms variation on the plate fog) were computed from the digitized frame of the master plate. The master list contains a little less than 100,000 detections at an 8σ level. Visual inspection of the detections against the digitized plate confirmed that no obvious stars will be left-out of the master list, even in cases of relatively high crowding.

Figure 1. Proper-motion error *vs.* V magnitude. Upper panel is for Galactic longitude, lower panel is for Galactic latitude. Note the rapid increase in the errors for $V > 18$.

This master list was then used to "feed" the Yale Image Centering routine described by Lee & van Altena (1983), which provides image centers, instrumental magnitudes and centering error estimates.

The next step was to reduce all of the plates to the master plate. No preliminary corrections for atmospheric refraction or distortion were performed in this solution. Refraction is likely to be an important effect, particularly for the first-epoch plates. However, this effect would be absorbed in the plate constants when converting to the master plate. The centered list on each plate was converted to the master plate using interactive software designed to recognize and isolate outliers, and to include distortion terms also in an interactive way until the residuals show no systematic trends.

The plate transformations described above indicate that we are indeed able to reach the expected level of accuracy. For example, plate-to-plate transformations between pairs of same-epoch plates have an rms scatter of 35 mas (i.e., 25 mas on each plate). On the other hand, transformations between first and second epoch plates indicate an rms dispersion of 80 to 100 mas. This higher dispersion is due to the proper-motion dispersion of the stars: For a population of velocity dispersion of 120 km/sec at 8 kpc, we expect an rms dispersion of 75 mas (21 yr baseline). Convolving the 75 mas with our measurement error gives our measured 80 mas dispersion. Evidently, the full analysis (including a pre-correction for optical distortion and atmospheric refraction) will give more precise results, but these preliminary reductions show that we can achieve the required accuracy from the available plate material. Once all the plates had been transformed to the master plate, and distortions had been removed, we computed the proper-motions by performing a *weighted* least-square linear fit to position *vs.* time, taking into account the individual plate solutions. This solution gave not only proper-motions but also error estimates for the derived motions. The individual proper-motion errors were computed from the scatter of

the residuals about the best-fit line as well as from the formal error of the slope in the linear fit. Figure 1 shows our proper-motion errors in Galactic longitude (μ_l) and latitude (μ_b) as a function of apparent V magnitude. For $V > 18$ the errors increase sharply. Also, we have very few objects with $V > 20$, mainly because of the magnitude limit for the 1st-epoch 84-inch plates. The use of the 200-inch plates will allow us to go to $V \approx 22$ for a selected sample of stars. Table 1 indicates the mean proper-motion errors in μ_l and μ_b as a function of V magnitude, as well as the number of stars in each magnitude interval. For $V > 18$ the errors become of the same order as the expected proper-motion dispersion ($\Sigma_\mu \approx 3\ mas/yr$). At this magnitude (or fainter), the sample with proper-motion errors less than about 1 mas/yr will only contain objects far from the mean error, and their errors are probably not very well determined. This translates into a spuriously large proper-motion dispersion for the fainter objects (see Table 2).

Table 1. Proper-motion error *vs.* V magnitude.

Magnitude range	Number of stars	σ_{μ_l} mas/yr	σ_{μ_b} mas/yr
$14.0 \le V < 16.0$	1530	0.75	0.69
$16.0 \le V < 17.0$	3944	0.91	0.88
$17.0 \le V < 17.5$	3023	1.47	1.44
$17.5 \le V < 18.0$	4102	2.18	2.13
$18.0 \le V < 18.5$	5904	3.12	3.05
$18.5 \le V < 19.0$	6392	4.10	4.00
$19.0 \le V < 22.0$	6287	5.32	5.23

3. Analysis of the proper-motions

The vector-point diagram for proper-motion error cuts at 1 mas/yr is shown in Figure 2. This figure compares well with Figure 1 in Spaenhauer et al. (1992). This suggests that the proper-motion dispersion for these two fields is approximately the same, as it is indeed the case (Table 2). The combination of a large sample and small measurement errors means that the proper-motion dispersions are known with great accuracy. Following Spaenhauer et al. (1992) the true (error-corrected) proper-motion dispersion, Σ_μ, is given by:

$$\Sigma_\mu^2 = \frac{1}{(n-1)} \sum_{i=1}^{n} (\mu_i - \bar{\mu})^2 - \frac{1}{n} \sum_{i=1}^{n} \sigma_{\mu_i}^2 \tag{1}$$

where n is the sample size, μ is one component of the proper-motion, and σ_{μ_i} is the error of a single proper-motion measurement. The error in Σ_μ in any subsample of n stars is given by:

$$\xi_\Sigma = \left(\frac{1}{2n} \Sigma_\mu^2 + \frac{1}{2n^2 \Sigma_\mu^2} \sum_{i=1}^{n} \frac{\sigma_{\mu_i}^4}{n_i} \right)^{1/2} \tag{2}$$

Figure 2. Vector-point diagram for objects with errors less than 1 mas/yr in each coordinate. This Figure compares very well with Figure 1 in Spaenhauer et al. (1992)

where n_i is the number of plates on which star i is measured. Spaenhauer et al. (1992) measured proper-motion dispersions of approximately 3 mas/yr. The above equations show that for a typical error of 0.5 mas/yr for a single measurement (Spaenhauer et al.'s level) our results would be unaffected by measurement errors. For subsamples of 200 stars, we estimate that the error in each subpopulation dispersion would be approximately 0.1 mas/yr (4 km/s at the distance of the Galactic bulge).

We have computed (intrinsic) proper-motion dispersions along Galactic longitude (Σ_{μ_l}) and latitude (Σ_{μ_b}) using Equations (1) and (2). In order to properly handle outliers, dispersions were determined in an iterative way following a procedure similar to the technique of outlier elimination using probability plots (Méndez & van Altena 1996). The results for the dispersions are shown in Table 2.

Table 2 shows how important it is to have a large sample of small-error proper-motions; the dispersions are determined with very high accuracy, typically the errors are less than 2%. Also, it can be seen that the proper-motion dispersion *does not* seem to change with apparent magnitude within the uncertainties (except for the large-error bin at $18 \leq V < 22$). There may be an indication that Σ_{μ_l} is slightly increasing with apparent magnitude, but the change is only at the 2σ level. Since we *do* expect to see a mixture of populations along the line-of-sight, each with different dispersion and mean rotational motion, this result implies that the contamination by these populations is rather minimal. The stellar ratio of disk/bulge, thick-disk/bulge, and halo/bulge is expected to change as a function of V magnitude, and so, therefore, is the proper-motion dispersion. We do not expect the disk or thick-disk to make a very large contribution (e.g., at Baade's window their contribution is less than 20%, and our field is at twice the Galactic latitude). However, we *do* expect to have a rather significant contribution from stars in the inner halo, which we do not seem to

detect. Table 2 also shows that the proper-motion dispersions Σ_{μ_l} and Σ_{μ_b} *are*

Table 2. Intrinsic proper-motion dispersion *vs.* V magnitude (only stars with errors less than 1 mas/yr in each coordinate included in solutions).

Magnitude range	No. stars in l	Σ_{μ_l} mas/yr	No. stars in b	Σ_{μ_b} mas/yr
$14.0 \leq V < 16.0$	1136	3.279 ± 0.069	1136	2.811 ± 0.059
$16.0 \leq V < 16.5$	1442	3.272 ± 0.061	1438	2.872 ± 0.053
$16.5 \leq V < 17.0$	1211	3.432 ± 0.070	1206	2.674 ± 0.055
$17.0 \leq V < 18.0$	1299	3.464 ± 0.068	1293	2.748 ± 0.054
$18.0 \leq V < 22.0$	236	5.293 ± 0.244	238	5.270 ± 0.240
$14.0 \leq V < 18.0$	5088	3.378 ± 0.033	5077	2.778 ± 0.028
Spaenhauer et al.	429	3.2 ± 0.1	429	2.8 ± 0.1

different in Galactic latitude and longitude at a 14σ level, which is a much more definitive result than that of Spaenhauer et al.'s (shown on the last line of Table 2), who suggested differences at the 3σ level. On the other hand, our results do agree with Spaenhauer et al.'s results within their rather large uncertainties in both Σ_{μ_l} and Σ_{μ_b}.

The interpretation of the values listed in Table 2 in terms of velocity dispersions for the bulge stars is complicated due to the expected contamination from halo stars. A simple two-component model predicts that the velocity dispersions for bulge stars in Galactic longitude and latitude (Σ_{B_l} and Σ_{B_b} respectively) are given by:

$$\Sigma_{B_l}^2 = (1+x)\Sigma_l^2 - x\Sigma_{H_l}^2 - \frac{x}{1+x} < V_B >^2 \tag{3}$$

and

$$\Sigma_{B_b}^2 = (1+x)\Sigma_b^2 - x\Sigma_{H_b}^2 \tag{4}$$

where Σ_l and Σ_b are the total velocity dispersions in Galactic longitude and latitude respectively, Σ_{H_l} and Σ_{H_b} are the halo velocity dispersions in Galactic longitude and latitude, $< V_B >$ is the mean rotation for the bulge, and x is the ratio of the number of halo to bulge stars in our sample.

Assuming 8.5 kpc as the distance to the Galactic center, and the mean values derived from Table 2, Equations (3) and (4) imply that $\Sigma_{B_l} \approx 140\ km/s$ and $\Sigma_{B_b} \approx 120\ km/s$. The larger Σ_{B_l} is consistent with rotation broadening and anisotropy of the Galactic bar (Zhao 1996, Zhao et al. 1996), but it does not necessarily argue for triaxiality. Zhao et al. (1994) have shown that only a strong *vertex deviation* of the bulge velocity ellipsoid (i.e., a non-zero cross-term $< V_r V_l >$) will be a definitive indication of triaxiality.

4. Conclusions and the future

We can obtain proper-motions for a large sample of bulge stars with errors small enough to allow a meaningful kinematical study of the bulge. It is found

that the proper-motion dispersion in our field is comparable with that found by Spaenhauer et al. (1992) in Baade's window. Our dispersions are consistent with broadening by rotation and anisotropy of the Galactic bar as predicted by the dynamical models of Zhao et al. (1996).

Radial velocities from our spectroscopic survey will be extremely important as a complement to the proper-motions to confirm the presence of a bar. Triaxiality will take the form of a vertex deviation in the Σ_r vs. Σ_l plane, as suggested from the Spaenhauer et al. data analysed by Zhao et al. (1994), and from a larger spectroscopic follow-up of Spaenhauer et al.'s sample by Rich et al. (1996).

If the bulge collapsed and spun up as metallicity increased, we should see Σ_r and Σ_b decrease with higher metallicity (Minniti 1993, 1996). In a rapidly rotating population, integration through the line of sight will reveal that Σ_l will be artificially broadened (Zhao et al. 1994, 1996). Applied to our large minor-axis sample this analysis will help constrain the formation/enrichment history of the bulge.

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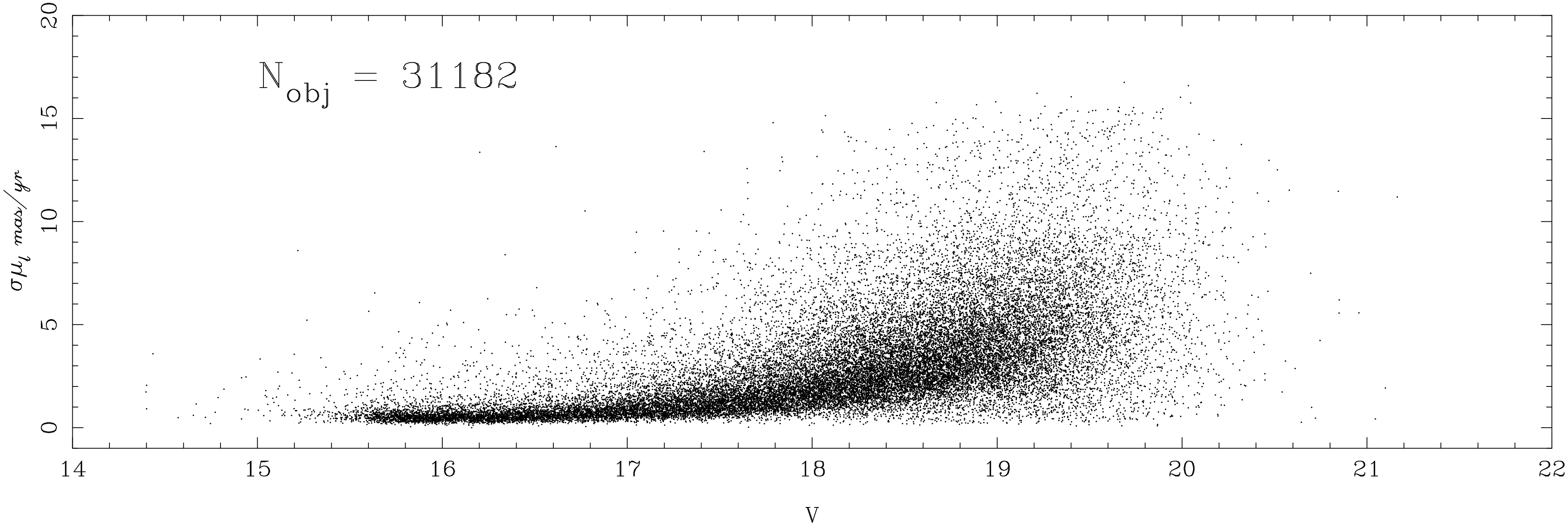

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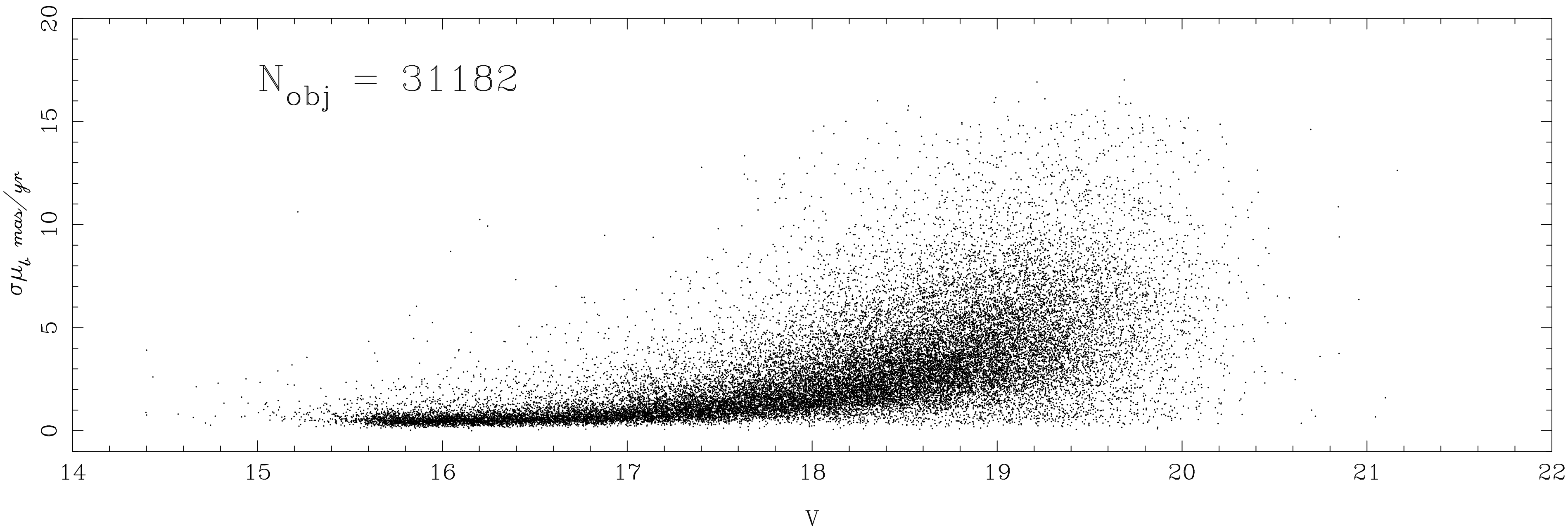
V



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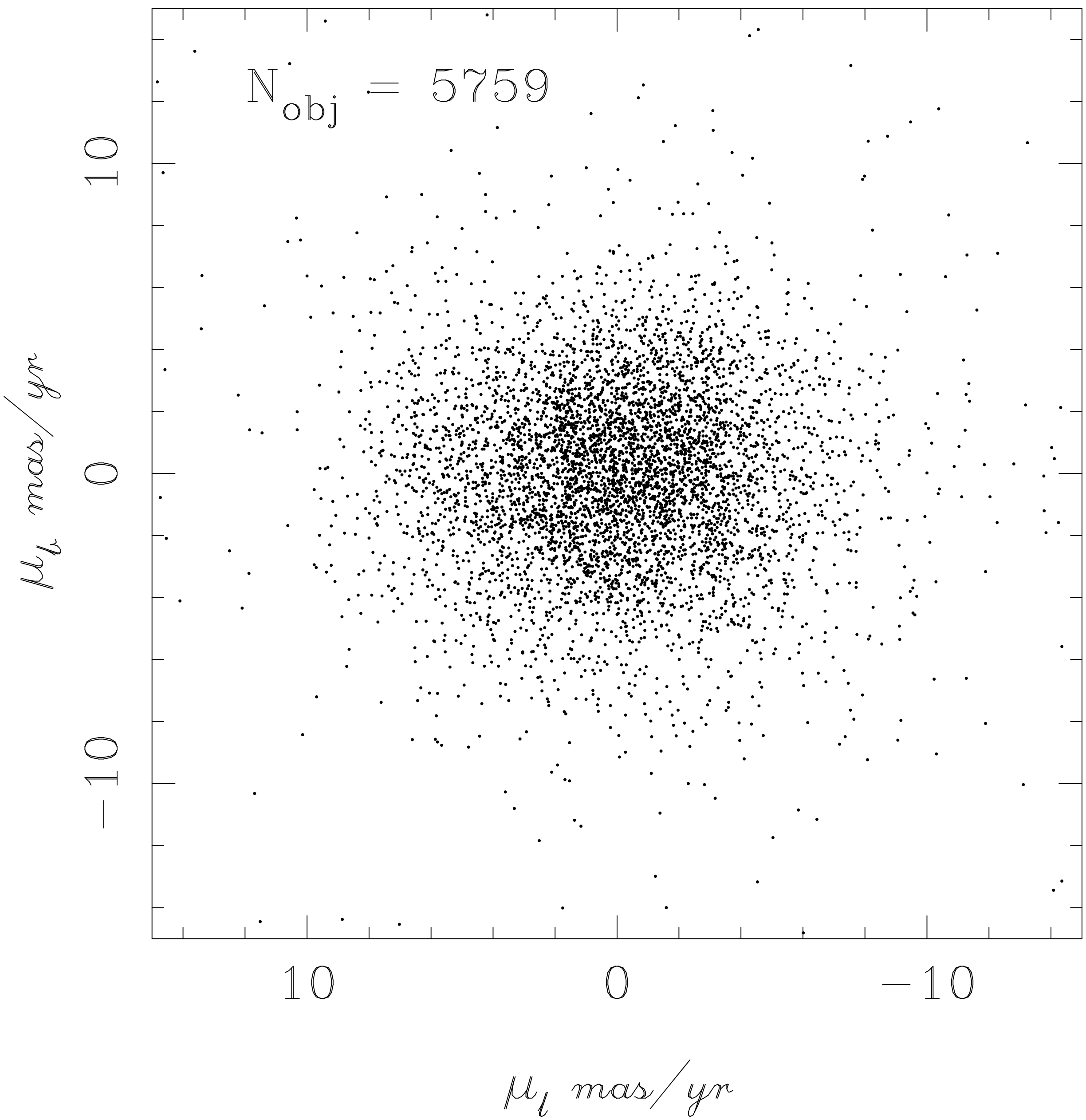

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μ_b mas/yr
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